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Depth Discrimination of a Crowded Line Is Better When It Is More Luminant Than the Lines Crowding It

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Observers usually cannot discriminate the relative depth of a crowded feature with respect to crowding features about 2 arc min distant if all the features have the same luminance. However, stereo thresholds significantly less than 20 arc sec are obtained when the crowded feature is about twice as luminant as the features crowding it. The thresholds depend only upon the ratio of the luminance of the target feature to the luminance of the crowding features and are independent of the absolute luminance of the features. With further increase in the relative luminance of the target feature, the performance eventually deteriorates and this deterioration is not due to difficulty in seeing the features which were individually clearly visible for all the luminances tested. The closest spacing of local crowded features that still allows good stereo discrimination is about the same as the spatial resolution attainable for many luminance-based non-stereo tasks.

Stereopsis Binocular vision Disparity interactions Depth perception Stereoacuity

INTRODUCTION

Stereoacuity thresholds increase very rapidly as features become closer together than about 5 arc min and are essentially infinite for separations less than 2.5 arc min (Westheimer & McKee, 1979). Can good stereoacuity with thresholds less than 20 arc sec ever be attained for features closer than about 2 arc min? To our knowledge this has never been definitively demonstrated. In this paper we examine this question by exploring the role of relative luminance and conspicuity of the test features in improving depth discrimination judgments when the stimulus elements are closely spaced.

Beside the high stereoacuity thresholds, interactions in the disparity domain are also evident when the stimulus elements are closely spaced. Westheimer found that adjacent features with a given disparity difference appear to approach each other more closely in depth (as if the two features attracted each other in depth) when their lateral separation is less than 2–8 arc min and to recede from each other in depth for larger separations between the features (Westheimer & Levi, 1987). A review of some of the distortions that occur with such stimuli is given by (Foley, 1991) who concludes that "in most cases not enough is known either about the phenomena or the models to say how well the models account for these effects" (p. 88). The models proceed by matching the corresponding features in the left and the right images, and if wrong matches are made, incorrect effective disparity is ascribed to the stimulus elements. The interaction phenomena do not appear to correspond to incorrect matches.

An effect that may be closely related to the interaction phenomena is that of disparity averaging (also called depth mixture or averaging): if random dot patterns depicting surfaces at two different depths are superimposed, a single surface at an intermediate depth may be perceived (Kaufman, Bacon & Borroso, 1973). The perceived depth varies with the relative luminances of the stimulus elements. Foley found (Foley, 1976) similar results using disparate vertical lines as stimulus elements. The perception of a single intermediate surface has been attributed to processes occurring at the level of disparity feature extraction by Parker and Yang (1989). They proposed to explain disparity averaging by assuming that stereopsis occurs when "... local features within the monocular images are extracted from a region covering several photoreceptors (by low-pass filtering of the image), thus effectively pooling together the information that could potentially define the component disparities as separate". Stevenson *et al.* (1989), though generally agreeing with this interpretation, pointed out that although the thick surface produced by two planes appears to have a disparity which is the "average" of the disparities of the individual planes, the resulting average

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surface can be distinguished from a single surface, since the surface appears thickened when the disparity difference between the planes is greater than about 15 arc sec. The disparity-averaging region suggested by Parker and Yang and others is about 4–5 arc min.

Westheimer and Levi, on the other hand prefer to keep the component disparities separate. They concluded that "if the concept of 'pooling' of disparity is invoked to account for the affinity of seen depth of closely-adjacent stimuli, the signals involved cannot be simply those of light weighted by disparity, but must be associated with individual features". Perhaps the rapid increase in relative disparity discrimination thresholds for test features that are crowded by other stimulus elements with respect to which the depth judgment is made is due to a disparity averaging or disparity interaction phenomenon. When features are only a few minutes apart, it is possible that the crowded target and the crowding adjacent comparison features affect each other's perceived depth either by pooling, or are disparity-averaged to form a composite feature. If there are remote comparison features in the stimulus with respect to which depth judgments of the composite feature can be made, stereoscopic thresholds might be governed by the separation between the composite feature and the remote comparison features and not by the separations among the components of the composite feature. To insure that depth is actually being judged for small separations, there should be no additional remote comparison features beside those that are closely spaced. The stimulus used in Expt 1 satisfies this requirement.

METHODS

Stimuli were presented stereoscopically on a pair of Hewlett–Packard vector oscilloscopes (HP 1345) with a fast white P4 phosphor using orthogonal polarizing sheets allowing only one oscilloscope screen to be visible to each eye. A beam-splitting pellicle was used to superimpose the images of the two screens. The luminance values were measured with a Pritchard 1980B spectrophotometer. Luminance values were measured for light reaching the spectrophotometer through the polarizers in front of each of the oscilloscope screens, the beam splitting pellicle, and the polarizers placed in front of the observers' eyes. The relative luminance values for the paths to the left and the right eyes differed by less than 1% and the values reported here are averages of the two values. The viewing distance was 9.76 m for all of the experiments except Expt 5 and at this distance the angular width of a line on the monitors was about 0.4 arc min. The viewing distance for Expt 5 was 3.3 m and at this distance the width of lines and dots was about 1 arc min. For ease of programming and because of hardware limitations, the luminance of the test line was varied by controlling the number of times it was drawn relative to the number of times the comparison features were drawn. For example, in Expt 1 the stimulus consisted of three vertical lines, each 12 arc min long, and when the two comparison lines were drawn three times for every time the middle test line was drawn, the luminance of the test line was measured to be 0.28 times the luminance of the comparison lines, and when the test line was drawn three times for every time the two comparison lines were drawn the test line's luminance was measured to be 2.5 times the luminance value of the comparison lines. When the test line was drawn five times for every time the comparison lines were drawn the test line's luminance was measured to be 4.2 times the luminance value of the comparison lines. Data were collected for three different luminance values for the comparison lines: 7.1 ± 0.5, 10.1 ± 0.7 and 14.5 ± 1.0 cd/m^2 when a single vertical line was measured through a 6 arc min circular aperture from a distance of 3 m. For these values of the luminance the lines appeared to be dim, bright and very bright on a dark background. The luminance of the background was less than 1 cd/m^2. Even for the dim lines the luminance contrast was well above detection threshold. For each luminance value of the comparison lines, the luminance of the middle target line could be set to 0.28 ± 0.04, 0.43 ± 0.06, 1.0 ± 0.15, 1.70 ± 0.18, 2.5 ± 0.22, 3.3 ± 0.28, and 4.2 ± 0.37 times the luminance value of the comparison lines. The confidence limits for the luminance ratios are the standard deviations computed from at least 20 measurements taken over 20 different days.

A two-alternative forced-choice paradigm using the method of constant stimuli was used for all of the experiments. The target feature was a vertical line 12 arc min long. The relative disparity of the target was randomly selected from a set of six different disparities, three crossed and three uncrossed, in equal increments with respect to the disparity of the comparison features which was the same for all of the experiments. The task was always to specify whether the target was nearer or farther than the comparison features. A horizontal line 3 arc min long was shown 10 arc min below the test line for 20 msec as an error signal if an observer's response was "farther" for crossed disparities or "nearer" for uncrossed disparities. Each run consisted of 180 trials and a minimum of four runs for each condition were conducted. For nearly all of the conditions reported, performance improved significantly with practice so that additional runs had to be conducted to achieve asymptotic performance. The thresholds reported are the averages of the last four "asymptotic" values. For any given luminance ratio data was always collected with a decreasing separation between the lines. All the observers tested required at least 10 runs for separations less than 1.75 arc min to reach asymptotic values. Each trial was at least 3 sec long with the stimulus being presented for 1 sec. An empty dark field was presented for 250 msec before and after each stimulus presentation. For the rest of the time, a single dot 1 arc min in diameter was shown in the middle of the screen as an inter-stimulus pattern. Only the stimulus was visible in the darkened room while data were being collected except for part of Expt 1, in which stereoacuity was measured with a stimulus consisting of only two vertical lines. The experiment was done when the ceiling fluorescent lights were on and also when they were off. For all the experiments the percent of responses reported as nearer, was fitted to an integral of a Gaussian using probit analysis to obtain a stereoscopic threshold, defined as half the increment in the relative disparity of the target feature required to increase the response from 25% to 75%. Judging the depth of a single isolated feature requires discrimination of absolute disparity and usually yields thresholds greater than 50 arc sec, values much larger than measured for discrimination of relative disparity (Kumar & Glaser, 1992). Stereoacuity thresholds significantly smaller than 50 arc sec are likely to result from relative disparity discrimination which requires at least two effective stereo features. When observers' thresholds were greater than 50 arc sec, they practiced for six runs or 1080 trials to determine whether their thresholds would improve with practice to be less than 50 arc min, although we did not attempt to measure these thresholds accurately. If there was evidence of improvement, additional runs were conducted to determine the asymptotic thresholds. In these experiments we wanted to determine only whether discrimination of the relative disparity of crowded features could be improved.

All of the observers were undergraduate students with normal vision when using corrective eyeglasses or contact lenses if necessary. The observers always wore glasses and not contact lenses when collecting data because they reported stress and fatigue when conducting runs with contact lenses for sessions longer than about half an hour. Most of the data was collected in sessions of 1 hr at a time. All of the experiments were also conducted by one of the authors (TK) who verified all the results reported here, although his results are not included in the reported data.

EXPERIMENTS AND RESULTS

In the first experiment we first confirmed the published results (Westheimer & McKee, 1979) using a stimulus that consists of a horizontal row of three equally luminant vertical lines. When the separation between the middle target line and each of the two flanking lines is 3 arc min or less, the stereoscopic threshold for the central test line is significantly greater than 20 arc sec. However when the test line is not crowded by two flanking lines but has only one comparison line, stereoscopic thresholds less than 20 arc sec may be obtained when the two equally luminant lines are as close as 1 arc min. At this small separation observers can distinguish two lines from a single line, but they do not see any open gap between the two lines. We also find that stereoscopic thresholds depend on the relative luminance of the test and flanking lines only when their separation is less than 5 arc min. For separations less than 5 arc min, stereoacuity thresholds are larger when the luminance of the middle target line is less than that of the flanking comparison lines. As the luminance of the middle line is increased, the stereo performance improves and finally begins to degrade with further increases in the luminance of the line. We find that when the middle test line is more luminant than the flanking lines, stereoscopic thresholds significantly less than 20 arc sec may be obtained by experienced observers for separations as little as 1.5 arc min between neighboring lines (Figs 1–3).

In the second experiment, two vertical flanking lines were added each 7 arc min away from the central crowded test line [Fig. 4(A)] as remote comparison features. Increasing the luminance of the crowded target line improves performance even more in the presence of these remote comparison lines. The three central closely spaced vertical lines seem to form a perceptual composite object quite readily. Perhaps the improvement in stereo thresholds is due to the possibility that the perceptual task is judging depth of the composite object with respect to the remote features. In Expt 3 the target line is crowded by either luminous rectangles or closely packed vertical lines [Fig. 4(B, C)]. These comparison features do not appear to be grouped into a composite object whose depth could be judged with respect to some remote features as in Expt 2. Stereoacuity thresholds are still very low when the target line is more luminant than the comparison features. Perhaps the only effect of changing the luminance of the test line is to make it more conspicuous. Experiment 4 shows that conspicuity of the target is insufficient for good performance. Stereoacuity thresholds are lower when the target is more luminant for various configurations of the comparison features [Fig. 4(D–F)] that appear to make the vertical test line conspicuous, although performance is better for some configurations than for others. In Expt 5, we show that the stereo thresholds are lower for extended crowded features than for small isolated features like 1 arc min diameter dots, although when the isolated 1 arc min diameter dot is more luminant than the surrounding crowding features, stereoacuity thresholds are low and there is little evidence of disparity averaging.

Experiment 1

The stimulus consisted of three vertical lines, each 12 arc min long, and the task was to judge whether the middle line was closer or farther away than the two flanking lines. The spacing of the lines and the luminance of the middle line with respect to the others were varied in this experiment, but held constant during each run. The middle line bisected the distance between the two outer flanking or comparison lines. The results obtained for one of the observers (EO) for the three luminance values of the comparison lines at three different separations between the test and the comparison lines are shown in Fig. 1. The results for the other observers were very similar to EO in that the measured thresholds depended only upon the ratio of the luminance of the middle target line to the luminance of the flanking comparison lines and were independent of the absolute luminance of the comparison lines. Because of this, the results for the three different luminance values (see Methods above) of the comparison lines were averaged. These average stereoacuity thresholds for

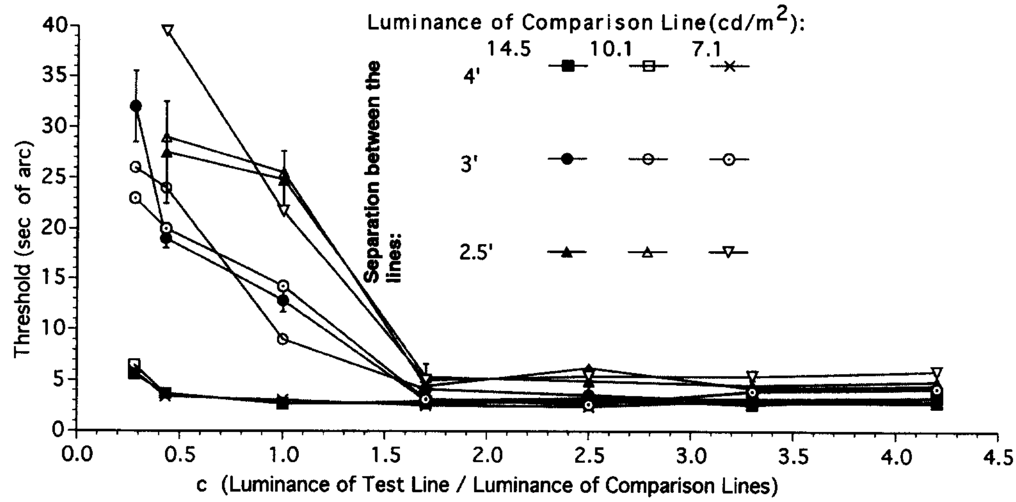

FIGURE 1. Stereoscopic thresholds for observer EO as a function of c, the ratio of the luminance of the target line to that of the comparison lines. The three parallel vertical lines were 12 arc min long and were arranged as in the center of Fig. 4(A). The middle target line bisected the separation between the outer lines. Thresholds above 50 arc sec were not precisely measured. Data for three different luminances and three different separation between the lines are shown. Data for the other observers was similar in that the thresholds depended only upon c and were independent of the absolute luminance of the comparison lines.

the three observers are shown in Fig. 2. In Fig. 3 the average stereoacuity thresholds for the three observers are replotted as a function of separation between the target line and comparison lines when the luminance of the target line and comparison lines were equal. In the same figure the minimum average stereoacuity threshold obtained for any tested luminance value of the middle line has also been plotted for all three observers. Stereoacuity for very closely spaced lines is seen to improve significantly as the luminance of the middle line increases. With further increase in the luminance of the middle line, the performance eventually deteriorates. Even for the largest luminance ratios tested, the flanking lines were clearly visible and the deterioration in performance was not due to difficulty in seeing either the target or the comparison lines.

We also measured performance when the right flanking line is not shown and the two lines have the same luminance. Westheimer and McKee (1979) have reported results on a similar task. They measured stereoacuity thresholds for two squares, each 2 arc min on a side, at different separations between the squares. For two of their observers (GW, and SM; see their Fig. 2) they report thresholds of about 20 arc sec for a separation of 2 arc min between the centers of the squares. At this separation there is no gap between the squares and the task is effectively to judge whether a vertical edge of a filled rectangle 2 arc min high and 4 arc min wide is closer to or farther from its other vertical edge 4 arc min away. We used lines that were about 0.4 arc min wide (smaller than the width of the line spread function) and less than 5 arc min apart. We made these measurements when the ceiling fluorescent lights were on and when they were off. When the overhead lights were on, the open box covering the supporting frame of the beam-splitting pellicle located in front of the two oscilloscopes (oriented at 90 deg with respect to each other) was visible and its edges were the features nearest to the two stimulus lines seen in the center. The horizontal separation between the lines and the edges of the support frame was 13 arc min, and the lines had about 0.5 arc min uncrossed disparity with respect to the edges of the frame. The frame kept nearly all of the light from the ceiling fixtures away from the oscilloscope faces. The luminance of the oscilloscope faces with no displayed stimulus and with overhead lights on was still less than 1 cd/m^2. We measured the stereoacuity thresholds of closely spaced lines when the ceiling fixtures were on and when they were off to assess the contribution of remote features. We reported previously that the disparity discrimination thresholds of a single line with room lights on was about 35 arc sec and with room lights off, about 55 arc sec (Kumar & Glaser, 1992). If the thresholds for relative disparity discrimination for the two-line stimulus are significantly less than 30 arc sec, the task must be different from the disparity discrimination of a single composite object with respect to remote features, and the remote features actually improve the judgment of the depth of the composite object consisting of the closely spaced features. We also measured the separation for which the observers could not see a gap between two vertical lines, each 12 arc sec long. The luminance value of the lines was 14.5 cd/m^2 (see Methods above) and they were shown stereoscopically with zero relative disparity. Starting with an initial separation of 4 arc min between the two lines, observers were asked to adjust the separation so that they could no longer see a gap between the lines. Starting with two superimposed lines, observers were also asked to increase the separation until they could just see a gap between the lines. The value reported

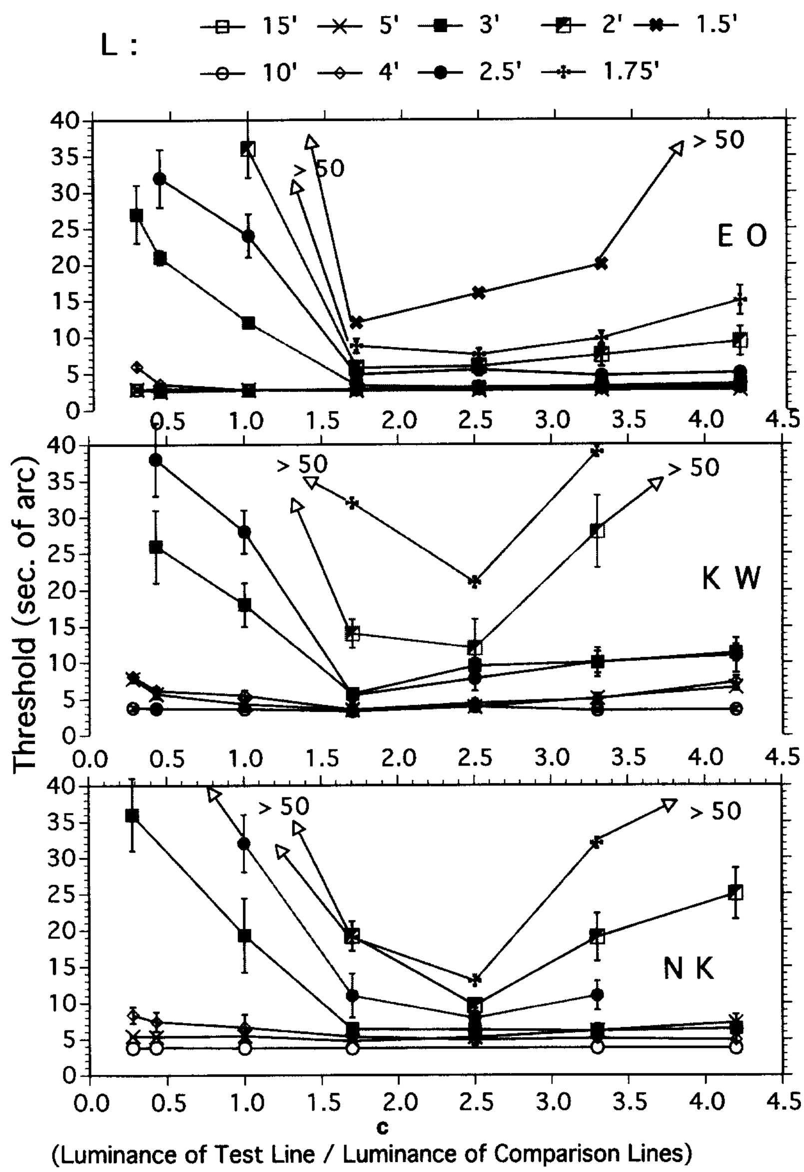

FIGURE 2. Stereoscopic thresholds for three observers as a function of the separation between the middle target line and the outer two flanking lines, and as a function of c, the ratio of the luminance of the target line to that of the comparison lines. Measurements were made for three different luminance values of the comparison lines. Since the thresholds depended only on c as shown in Fig. 1, the average of the measurements at the three different luminances is shown. Each data point shown is the average of at least 12 runs (four runs at each of the three luminance values of the comparison lines) with 180 trials in each run. The error bars are ± 1 SD of the thresholds from the multiple runs.

is the average of these two values each measured five times. Although the observers did not see an open gap between the lines at the reported separation, they could distinguish between two lines and a single line when tested with a forced-choice paradigm. The value reported in the literature for discriminating whether there is one line or two is 25 arc sec which is much smaller than the average value, about 1.3 arc min, that we measured for judging the presence or absence of an open gap (Boff & Lincoln, 1988, Section 1.602, Table 2, p. 199). The average value we measured is indicated as a vertical arrow in Fig. 2 and demonstrates that observers can discriminate the relative disparity of a crowded target line if it is sufficiently more luminant than the comparison lines even when they can barely resolve it from the comparison lines.

As shown in Fig. 3, it is not the separation between two features itself that is the limiting spatial distance for stereopsis; the relative disparity of two equally luminant and isolated lines that are a mere 1 arc min apart within a visually rich environment can be discriminated reliably by experienced observers, even when they are unable to see a gap between the two lines. Experienced observers have difficulty in judging depth when a feature is "crowded" by other features, or the stimulus is very sparse (one or two lines in the entire visual field). Increasing the luminance of the crowded feature relative to the crowding features improves performance significantly. Observers can discriminate the relative disparity of a line that is only 1.5 arc min away from the crowding lines even though

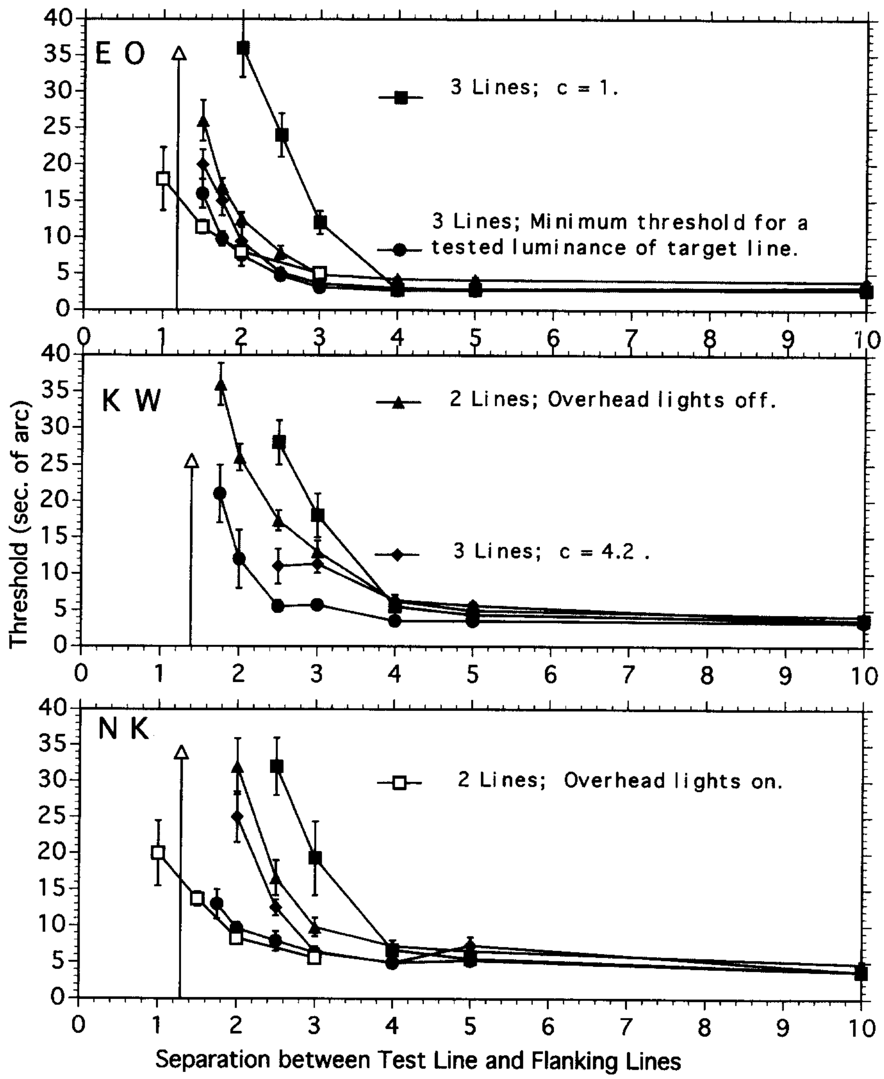

FIGURE 3. The data used in Fig. 2 for the three-line stimulus has been replotted as a function of the separation between the target line and the flanking comparison lines. For $c = 1$ thresholds below 3′ separation are above 20 arc sec and increase rapidly with decreasing separation between the lines. For some measured values of $c < 4.2$, thresholds less than 20 arc sec may be obtained for a separation of 1.5′ between the lines. For the stimulus with two lines the target line is not crowded by two flanking lines and stereoscopic thresholds less than 20 arc sec may be obtained for a separation of only 1 arc min between the lines when the overhead lights are on. When the overhead lights are off, stereoscopic thresholds are slightly worse. The vertical arrow marks the separation for which the observers were unable to see an open gap between two lines.

they are barely able to detect a gap between the lines under those circumstances.

Experiment 2

In Expt 1, the only comparison lines were adjacent to and barely separated from the target lines. Would the presence of remote additional comparison features help in discriminating the depth of the target line as suggested by the improvement in performance observed when the overhead lights are turned on? The stimulus A in Fig. 3 was used to study this question. The vertical lines were 12 arc min long and the target line was in the middle as before. The inner flanking lines were 1.75 arc min away from the target line and the outer two comparison lines were 7 arc min away. When all of the lines had the same luminance, observers were unable to discriminate the relative disparity of the target line and thresholds were estimated to be greater than 50 arc sec as shown in Table 1. This estimate is based upon at least six runs or 1080 trials for each observer. Under the assumption that the central three lines are treated as a single composite object and the effective disparity of this object is the average disparity of the three lines, which is one-third the disparity of the middle line for $c = 1$ where c is the ratio of the luminance of the middle line to the luminance of the closely-adjacent lines. Observers, with thresholds of 4 arc sec for separations larger than 4 arc min (see Fig. 2), should have thresholds for the disparity of the middle line of about 12 arc sec if they were treating the central three lines as a composite object and judging its depth relative to the outer lines 7 arc min away. Runs were also conducted for which the task was specifically to judge whether the central three lines as a group were closer or farther away than the outer two

TABLE 1. Stereoscopic thresholds for stimuli A–E described in Fig. 3

		Threshold (arc sec)		
Stimulus	Condition	EO	NK	KW
A	$c = 1.0$	>50	>50	16.8 ± 2.3
	$c = 2.5$	5.8 ± 1	5.2 ± 0.7	4.9 ± 0.5
	$c = 4.2$	4.2 ± 0.7	4.2 ± 0.5	3.9 ± 0.3
B	$c = 1.0$	24 ± 4	>50	18 ± 2.8
	$c = 2.5$	4.2 ± 0.4	6.2 ± 1.2	5.6 ± 0.9
C	$c = 1.0$	>50	>50	>50
	$c = 2.5$	5.5 ± 0.7	5.8 ± 0.8	6.3 ± 0.9
D	$c = 0.5$, 1.0 or 1.75	>50	>50	>50
E	Separation between target line and comparison lines: 1.5 arc min	5.3 ± 0.8	7.2 ± 0.9	8.3 ± 0.6
	Separation between target line and comparison lines: 2 arc min	4.8 ± 0.7	6.2 ± 1.2	6.6 ± 0.8

c given under condition is the ratio of the luminance of the target line to that of the comparison features. Stimulus A was used in Expt 2, stimuli B and C were used in Expt 3, and stimuli D and E in Expt 4. In A the task may have been equivalent to judging the depth of a composite object consisting of the target line and the inner two flanking lines with respect to the depth of the remote outer flanking lines. There did not appear to be any condensation into a composite object in stimuli B and C. Although, the vertical line was as conspicuously visible in stimulus D as in stimulus E, the thresholds for D were high and insensitive to changes in the luminance of the target line.

comparison lines. Thresholds were still larger than 50 arc sec. It is not obvious why depth averaging was not evident for these observers when the lines were of equal luminance. One of the authors' (TK) threshold for this task was measurable and was about 16 arc sec. Perhaps with additional practice the other three observers' performance would have improved. However, for $c = 2.5$ or 4.2 and a separation of 1.75 arc min between the target line and its immediate neighbors the observers' thresholds were significantly smaller than the minimum measured for $c = 1$ and a separation of 1.75 arc min with the three-line stimulus (see Fig. 2). The remote comparison lines do help in judging the depth of the more luminant crowded target line. However, it might not be the depth of the crowded line that is being judged, but rather that of a putative composite object consisting of the central three lines with respect to the depth of the two remote flanking lines that are 7 arc min away. The expected thresholds for such a composite object are slightly larger (because of disparity averaging with the closely-adjacent flanking lines with zero disparity) than those measured in Expt 1 for three lines that are equally luminant with a separation of 7 arc min between the lines. Those thresholds may be read off from Fig. 2 and are slightly lower than those obtained in this experiment. However, it is puzzling why disparity averaging is not evident for the three observers when the luminance of the three lines is equal.

Experiment 3

The three central lines in stimulus A might plausibly have been treated perceptually as a composite feature, and the remote features assistance to improving stereo thresholds might be limited to remote uncrowded composite features. However for stimuli B and C used in this experiment as shown in Fig. 4, an uncrowded composite feature may not be perceived. The middle target line was flanked by 10 lines for stimulus B, and by 6 lines for stimulus C. The separation between the target line and the nearest flanking lines was 1.75 arc min as before. The separation between the other flanking lines was 1 arc min in stimulus B and 2 arc min in stimulus C. Stimulus C was obtained by not showing four of the flanking lines displayed in stimulus B. Because of the close packing of the flanking lines, stimulus B was seen by the observers as a line between two uniformly luminous rectangles, while each flanking line could be seen individually in stimulus C. Stereoacuity thresholds were measured when the luminance of the target line was equal to that of the flanking lines and when it was 2.5 times greater as shown in Table 1. Two of the three observers could discriminate the relative disparity of the target line in stimulus B even when the luminance of the target and flanking lines were equal, while for stimulus C under the same conditions the thresholds were greater than 50 arc sec. Perhaps the outer edges of the perceived rectangles provided assistance in lowering the stereoacuity threshold, but the outer flanking lines in stimulus C do not appear to contribute similar assistance. When the luminance of the target line was 2.5 times that of the flanking lines, observers' performance improved significantly to about the same level as those measured for stimulus A. Therefore depth averaging with the adjacent features might also be taking place for stimuli B and C. However the separation of the outer flanking lines assures that even if the disparity of the target line is being averaged with that of the adjacent features, the resulting object is still crowded by the outer comparison lines.

Experiment 4

In all of the stimuli described so far, the crowding features were vertical lines of the same length as the

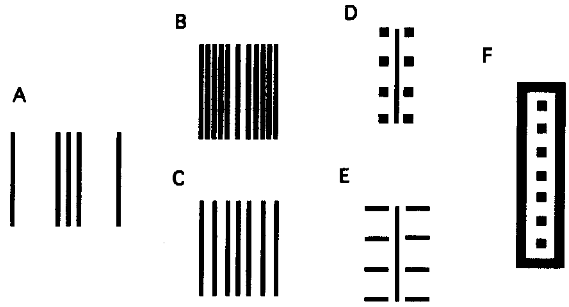

FIGURE 4. Stimuli used in Expts 2–5. The vertical lines in (A)–(E) are 12 arc min long. The lines for all the stimuli were about 0.4 arc min wide, and the dots were squares 1 arc min on a side. For stimuli (A), (B) and (C) the middle line is the target line and the separation between the center of the target line and the centers of the nearest flanking lines is 1.75 arc min. The separation between the center of the target line and the centers of the outer two flanking lines in (A) is 7 arc min. There were five comparison lines on either flank of the target line in (B), and the separation between the centers of these flanking lines was 1 arc min. Because of this small separation observers could not see the individual lines but saw the stimulus as a vertical line between two uniformly illuminated 5 × 12 arc min rectangles. Four lines were removed from stimulus (B) to generate stimulus (C) in which there where three comparison lines on either side of the target line, and the separation between the centers of the flanking lines was 2 arc min. The observers were able to see the individual flanking lines at this separation. In stimulus (D) the target line was flanked by eight squares, each 1 arc min on a side. The squares were aligned vertically with a vertical separation of 3 arc min between centers of the squares, and a separation of 1.5 arc min between the nearest edge of the squares and the nearest edge of the target line. The dimensions of stimulus (E) were identical to those of (D) except the squares were replaced by 3 arc min long horizontal lines when the separation between the nearest edge of the lines and the nearest edge of the target line was 1.5 arc min, and by 2.5 arc min long horizontal lines when the separation between the nearest edge of the lines and the nearest edge of the target line was 2 arc min. In stimulus (E) seven dots, each about 1 arc min diameter, were inclosed in a 6 × 24 arc min rectangle. The center of the nearest feature was 3 arc min away from the center of any dot. Stereoscopic thresholds obtained using these stimuli are given in Tables 1 and 2.

target line. Would similar effects be found if the crowding features were different, permitting easy differentiation of the target from the comparison features? Stereoacuity thresholds were measured using stimuli D, E, and F to answer this question. In stimulus D the target line, a 12 arc min vertical line, was flanked on either side by a column of 4 squares each 1 arc min on a side. The centers of the squares were 4 arc min apart vertically and horizontally. This meant that the horizontal separation between the target line and the nearest edge of any square was 1.5 arc min The squares and the line were of equal luminance (i.e. the speed and the intensity of the electron beam used to draw the lines and the squares was kept constant). Stereoacuity thresholds for this stimulus were greater than 50 arc sec and hence were not measured accurately. We did not detect any change in performance when the luminance of the target line was changed to either 0.5 or to 1.75 times the luminance of the comparison dots. Stimulus E was identical to stimulus D except that the comparison items were 3 arc min horizontal lines with a separation between the center of the target line and the inner end of the horizontal lines of 1.5 arc min. Stereoacuity thresholds were dramatically better than for stimulus D, even when the luminance of the target line was the same as the luminance of the comparison. When the separation between the center of the target line and the nearest end of the horizontal lines was increased from 1.5 to 2 arc min by replacing the 3 arc min horizontal lines with 2.5 arc min horizontal lines, there was a detectable improvement in the thresholds. Although the vertical line in stimulus D was conspicuously different from the comparison column of dots, observers were unable to judge the depth of the line. Stimulus E crowded the target at least as much as D, but the observers' performance was markedly better. Perhaps the outer ends of the horizontal lines provided a less crowded comparison feature, but then performance for stimulus B or C should also have been better. The crowding features in stimuli D and E are relatively sparse compared to those in stimuli B or C, and hence the difference in performance may not be attributed to sparseness itself. Reasons for the difference in performance probably should be sought in mechanisms that form composite features for such closely packed light distributions.

Experiment 5

In this experiment the target features consisted of 1 arc min diameter dots as sketched in stimulus F of Fig. 4. The stimulus contained seven dots equally spaced 3 arc min apart surrounded by a rectangular frame

TABLE 2. Stereoscopic thresholds of two observers for stimulus described in Fig. 3(F) were determined separately when the long dimension of the rectangular frame was horizontal, and when it was vertical

	Threshold (arc sec)			
	Horizontal		Vertical	
Condition	HS	BH	HS	BH
3	40 ± 7	39 ± 5	16 ± 2	30 ± 3
3 brighter	8.2 ± 1	7.5 ± 0.2	4.7 ± 3	5 ± 0.4
3 dimmer	Always seen behind		Always seen behind	
3,4	13.2 ± 2	13 ± 1	6.8 ± 0.7	24 ± 4
2,3,4	7.9 ± 0.5	10 ± 1.4	7.1 ± 1	14 ± 2
1,2,3,4	5.5 ± 0.4	7.5 ± 0.8	6 ± 0.5	15 ± 3
0–6	5.8 ± 0.6	8.0 ± 1	6.1 ± 0.9	17 ± 2
1,3,5	11 ± 0.8	24 ± 3	8.9 ± 1.2	36 ± 6
0,2,4,6	11 ± 0.7	14 ± 1.5	10.3 ± 0.8	21 ± 3
0,6	> 50	> 50	> 50	> 50

Thresholds for these cases are given in the columns labeled Horizontal and Vertical. The dots are assigned numbers 0–6 for convenience. The uppermost dot when the frame is vertical and the leftmost dot when the frame is horizontal are labeled zero. The rest of the dots were numbered sequentially so that the middle dot is "3" and the bottom dot for the vertical case and the rightmost dot for the horizontal case is "6". Equal non-zero disparities were given to the various dots listed under the column labeled "condition" in the table. For example, entry "2,3,4" means that only dots 2, 3 and 4 were given identical non-zero disparities and the rest of the dots had zero disparity with respect to the frame. The task was to state whether "anything" was closer or farther away than the rectangular frame. Condition "3 brighter" corresponds to the case in which dot 3 was about twice as luminant as the other dots and the rectangular frame, and condition "3 dimmer" corresponds to dot 3 being about half as luminant as the other dots and the rectangular frame.

6×24 arc min. The center of any feature nearest to the center of any dot was 3 min arc, or edge to edge dimension was about 2 min arc in this configuration. Thresholds were determined separately when the long dimension of the rectangular frame was horizontal, and when it was vertical. Thresholds for these cases are given in Table 2 in the columns labeled Horizontal and Vertical. Figure 4(F) shows the rectangular frame aligned vertically. The dots are assigned numbers 0–6 for convenience. The uppermost dot when the frame is vertical and the leftmost dot when the frame is horizontal are labeled zero. The rest of the dots were numbered sequentially so that the middle dot is "3" and the bottom dot for the vertical case and the rightmost dot for the horizontal case is "6". Equal non-zero disparities were given to the various dots listed under the column labeled "condition" in the table. For example, entry "3,4" means that only dots 3 and 4 were given identical non-zero disparities. The rest of the dots and the frame always had zero disparity. The task was to state whether "anything" was closer or farther away than the rectangular frame. The threshold for depth discrimination improves as the number of adjacent dots with identical disparity increases to span a separation of about 9–12 arc min in the horizontal case and about 6–9 arc min for the vertical case. If the luminance of a single dot was larger, about twice that of the other dots and the rectangular frame, the threshold improved markedly. If the single target dot was dimmer than the other features, the two observers always saw it as farther away than the rectangular frame and thresholds could not be estimated. If thresholds were determined by simple disparity averaging, the thresholds when dots 1, 3 and 5 are given disparity should be $\frac{5}{3}$ times the threshold when dots 1–5 were given disparity, and the threshold when dots 0, 2, 4 and 6 are given disparity should be $\frac{7}{4}$ times the threshold when all seven dots had disparity. The thresholds obtained were quite different than those expected from this simple reasoning.

Could the observers see every other dot in depth? After obtaining the threshold values, the two conditions "1,3,5" and "0,2,4,6" were shown with the dots being given a crossed disparity of 40 arc sec which was well above the threshold value of the observers. Preliminary runs were conducted to insure that the observers could detect and discriminate crossed and uncrossed disparity of 40 arc sec in this stimulus. Then both the conditions were shown in random order in a run, and the task was to discriminate between the two conditions. The observers were informed that the disparity was being given to every other dot, and that they would be shown either the odd dots only or the even dots only in front of the surrounding rectangle. Neither observer could distinguish between the two conditions. Then conditions "2,3,4", "1,3,5" and "0,2,4,6" with dot disparities of 40 arc sec were shown for a 1-sec presentation time each, and the observers were asked to describe what they saw. The observers could press a button and have the same stimulus presented as many times as they chose, but each presentation was restricted to 1 sec. Both the observers saw "something in the middle" in front for condition "2,3,4". They could not state whether it was 2, 3, or 4 dots "in the middle" that appeared in front of the rest of the stimulus. For the other two conditions, they saw all the dots in front of the rectangular figure. When dot 3 was brighter and had 40 arc sec crossed or uncrossed disparity, it was easy to see that only one dot was in closer or farther, respectively, than the other dots and the rectangular frame. The thresholds were low enough that depth averaging with adjacent dots or the frame did not seem be to occurring.

DISCUSSION

We have shown that the relative disparity of a line with respect to crowding flanking lines about 1.5–2 arc min apart and with different luminances can be discriminated reliably. The relative disparity of two uncrowded lines without flanking lines and about 1 arc min apart can also be discriminated readily. The acuity threshold, or lateral resolution, for lines of the same luminance and similar to those used in the stereo experiments is about 1.3 arc min. The relative luminances of the components of a stimulus do not affect stereoacuity thresholds when the features being compared are separated by more than 5 arc min, but are critical at smaller separations. In our experiments, the spatial resolution of stereoscopic vision means the smallest lateral separation of features in a stimulus which permits effective discrimination (thresholds less than 20 arc sec) of the relative stereoscopic depth of these features. In the present experiments, the stereo resolution for disparity discrimination is found to be about the same as the usual lateral resolution or somewhat larger, but less than twice as large.

The drop in stereo thresholds when the crowded feature is more luminant than the crowding features is unlikely to be explainable in terms of more precise localization of the matching feature using zero crossings or maxima or minima in a filtered representation. The reduction in stereo thresholds of crowded features is clearly evident even when the separation between stimulus elements is as large as 3 arc min (see Fig. 3). Various multi-channel spatial filters that have been proposed for visual processing should not have any difficulty in localising vertical lines of very high contrast (greater than 7 cd/m^2 on a background of less than 1 cd/m^2) and for separations of more than 1.5 arc min between the lines. Increasing the luminance of the middle line in a three-line stereo stimulus does not affect localization accuracy using maxima or zero crossings when the Laplacian of a Gaussian of central width less than 2.75 arc min is applied to a stimulus with a separation between the lines of 3 arc min. The smallest filter used by Grimson (1981) for determining corresponding zero crossings in the views of the two eyes is 1.33 arc min wide. Using coarser filters or decreasing the separation between the lines results in loss of relative localization of filtered features in the three-line stimulus as the luminance of the middle line is increased, and we approach the situation contemplated by Parker and Yang (1989) where only a locally composite feature is expected to be localized. In contrast, our results show that observers can judge the relative depth of fine local details and not only the composite of the three lines. Although in the analysis of Westheimer and Levi signals are associated with individual features, a process still needs to be specified for defining these features from the light distribution and for determining their relative localization and effective disparity.

It may not be feasible to apply the concept of the spatial resolution of stereoscopic vision defined above for our experiments to other experiments without a better understanding of the rules of disparity interactions and of the nature of stereo features and their relationship with monocular features. In our experiments the spatial resolution of stereoscopic vision of local targets has about the same value as the resolution of many monocular tasks, especially if components of the stereo stimulus have different luminances. Although there are many well established differences between the responses to luminance and stereo cues in psychophysical experiments, our experiments show for the first time that the spatial resolution of stereo is not much coarser than that of luminance-based monocular acuity. How are local features represented and how is disparity attributed to them? Are there other factors which can improve stereoscopic performance as do changes in the relative luminance of crowded features? These questions remain to be answered experimentally.

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